

Probing Quark Matter In Neutron Stars

M. Prakash^a

^aDepartment of Physics & Astronomy, State University of New York at Stony Brook,
Stony Brook, New York-11794-3800, U.S.A.

The presence of quark matter in neutron star interiors may have distinctive signatures in basic observables such as (i) masses and radii [1], (ii) surface temperatures versus age [2], (iii) spin-down rates of milli-second pulsars [3], and (iv) neutrino luminosities from future galactic core collapse supernovae [4]. I highlight recent developments in some of these areas with a view towards assessing how theory may be confirmed by ν -signals from future galactic supernovae in detectors like SuperK, SNO and others under consideration, including UNO [5], and by multi-wavelength photon observations with new generation satellites such as the HST, Chandra, and XMM.

1. NEUTRINO SIGNALS

A proto-neutron star (PNS) is born following the gravitational collapse of the core of a massive star, in conjunction with a successful supernova explosion. During the first tens of seconds of evolution, nearly all ($\sim 99\%$) of the remnant's binding energy is radiated away in neutrinos of all flavors [6–8]. The ν -luminosities and the evolutionary timescale are controlled by several factors, such as the total mass of the PNS and the ν -opacity at supranuclear density, which depends on the composition and equation of state (EOS). Collins and Perry [9] noted that the superdense matter in neutron star cores might consist of weakly interacting quarks rather than of hadrons, due to the asymptotic freedom of QCD. The appearance of quarks causes a softening of the EOS which leads to a reduction of the maximum mass and radius [1]. In addition, quarks would alter ν -emissivities and thereby influence the surface temperature of a neutron star [2] during the hundreds of thousands or millions of years that they might remain observable with such instruments as HST, Chandra, and XMM.

Many calculations of dense matter predict the appearance of other kinds of exotic matter in addition to quarks: for example, hyperons or a Bose (pion, kaon) condensate [10, and references therein]. An important question is whether or not ν observations from a supernova could reveal the presence of such exotic matter, and further could unambiguously point to the appearance of quarks. The detection of quarks in neutron stars would go a long way toward the delineation of QCD at finite baryon density which would be complementary to current Relativistic Heavy Ion Collider experiments, which largely address the finite temperature, but baryon-poor regime.

An important consequence of the existence of exotic matter in neutron stars (in whatever form, as long as it contains a negatively charged component), is that a sufficiently

massive PNS becomes metastable [10,11]. After a delay of up to 100 s, depending upon which component appears, a metastable PNS collapses into a black hole [7,8]. Such an event should be straightforward to observe as an abrupt cessation of ν -flux when the instability is triggered.

In Ref. [4] we provide a benchmark calculation with quarks by solving the general relativistic ν -transport and hydrostatic equations (see [7,8]) with the EOS of [12] and ν -opacities of [13] as microphysical ingredients. In the left panel of Fig. 1, we compare ν -signals observable with different detectors for stars containing nucleons and quark matter (npQ stars). The two upper shaded bands correspond to estimated SN 1987A (50 kpc distance) detection limits with KII and IMB, and the lower bands correspond to estimated detection limits set to a count rate $dN/dt = 0.2$ Hz [8] in SNO, SuperK, and UNO, for a Galactic supernova (8.5 kpc distance). It is possible that this limit is too conservative and could be lowered with identifiable backgrounds and knowledge of the direction of the signal. The width of the bands represents the uncertainty in the $\bar{\nu}_e$ average energy due to the flux-limited diffusion approximation [7,8]. We conclude that it should be possible to distinguish between stable and metastable stars, since the luminosities when metastability is reached are always above conservative detection limits.

Our quark EOS [12], in conjunction with the baryonic EOS we used, was motivated to maximize the extent of the quark matter phase in a cold neutron star, and was limited by the necessity of producing a maximum mass cold star in line with accurate observational constraints ($M_G = 1.444 M_\odot$). Use of an alternative quark EOS that otherwise produces a larger maximum mass, delays the appearance of quarks and raises the metastability window to larger stellar masses [12]. Necessarily, this results in an increased timescale for metastability for a given mass, and a lower ν -luminosity when metastability occurs. Fig. 1 shows the relation between time to instability and M_B for the original case (thick solid curve) and a case (thin solid curve), in which the maximum gravitational mass of a cold neutron star is about $1.85 M_\odot$. For the latter case, the metastability timescales lie in a narrow range 40–45 s.

In the right panel of Figure 1, we show the metastability time- M_B relation found for matter containing hyperons (npH , dashed lines [7]) or matter with kaons (npK , dotted line [8]) instead of quarks. All three types of strange matter are suppressed by trapped neutrinos [10,12], but hyperons always exist in npH matter at finite temperatures and the transition to quark matter can occur at lower densities than that for very optimistic kaon cases [8]. Thus, the metastability timescales for npH matter can be very short, and those for npK matter are generally larger than for npQ matter. Note the relatively steep dependence of the metastability time with M_B for npH stars, which decreases to very small values near the maximum mass limit of hot, lepton-rich, stars. The thick npH and npQ lines, as well as the npK line, represent minimum metastability times for a given M_B as discussed above. The thin npQ and npH lines are for EOSs with larger cold, catalyzed maximum mass.

Clearly, the observation of a single case of metastability, and the determination of the metastability time alone, will not necessarily permit one to distinguish among the various possibilities. Only if the metastability time is less than 10–15 s, could one decide on this basis that the star’s composition was that of npH matter.

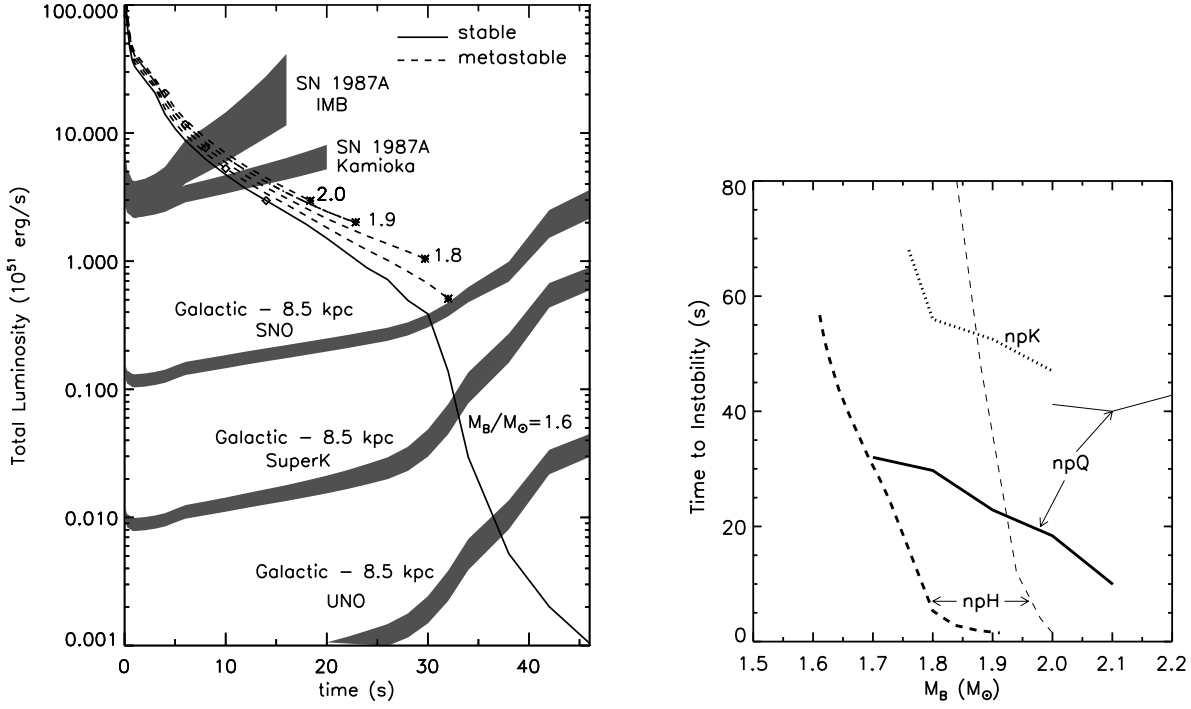


Figure 1. Left panel: The total ν -luminosity for npQ stars of various baryon masses. Shaded bands illustrate the limiting luminosities corresponding to count rates of 0.2 Hz for the indicated supernovae in some detectors. Right panel: Lifetimes of metastable stars versus the PNS M_B for various assumed compositions. Thick lines denote cases in which the maximum masses of cold, catalyzed stars are near $M_G \simeq 1.45 M_\odot$, which minimizes the metastability lifetimes. The thin lines for the npQ and npH cases are for EOSs with larger maximum masses ($M_G = 1.85$ and $1.55 M_\odot$, respectively).

Our conclusions are that (1) the metastability and subsequent collapse to a black hole of a PNS containing quark matter, or other types of matter including hyperons or a Bose condensate, are observable in current and planned ν detectors, and (2) discriminating among these compositions may require more than one such observation. This highlights the need for breakthroughs in lattice simulations of QCD at finite baryon density in order to unambiguously determine the EOS of high density matter. In the meantime, intriguing possible extensions of PNS simulations with npQ matter include the consideration of heterogeneous structures [14], quark matter superfluidity [15], and coherent ν -scattering on droplets [16].

2. MULTI-WAVELENGTH PHOTON OBSERVATIONS

In Ref. [2], the prospects of detecting baryon and quark superfluidity from neutron stars during their long-term (up to 10^6 years) cooling epoch was studied. Our assessment is that, from future photon observations of neutron star cooling, (1) one could constrain the smaller of the n - or Λ - pairing gaps and the star's mass, (2) deducing the sizes of quark

gaps will be difficult, (3) large q -gaps render quarks invisible, and (4) vanishing q -gaps lead to cooling behaviors which are indistinguishable from those of np or npH stars.

However, think this titillating thought ! The observation of a neutron star older than 10^6 year and hotter than $\sim 10^7$ °K signals quarks with large gaps in neutron stars !

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